

# Environmental impacts of forest production and supply of pulpwood: Spanish and Swedish case studies

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## Abstract

**Background, aim and scope** Forest operations use large amounts of energy, which must be considered when life cycle assessment (LCA) methodology is applied to forest products. Forest management practices differ considerably between countries and may also differ within a country. This paper aims to identify and compare the environmental burdens from forest operations in Sweden and Spain focused on pulpwood production and supply to pulp mills.

**Materials and methods** To perform the analysis, the main forest plantations were investigated as well as the most important tree species used in pulp mills in both countries: eucalyptus and, Norway spruce and Scots pine, were taken into account for the Spanish and Swedish case studies, respectively. Energy requirements for pulpwood production and supply to Spanish and Swedish pulp mills are evaluated in this paper. All forest operations from site preparation to extraction of felled wood to the delivery point at the roadside are included within the system boundaries as well as wood transport from forest landing to the pulp mill gate. Seedling and machinery production are excluded from the system boundaries due to lack of field data. The impact assessment phase was carried out according to the Swedish Environmental Management Council and, in particular, the

impact categories assessed in forest and agricultural LCAs (global warming, acidification, eutrophication and photochemical oxidant formation) were analysed. SimaPro 7.10 software was used to perform the impact assessment stage. **Results** Different types of wood are produced in both case studies: softwood in Sweden and hardwood in Spain, with higher production of round wood and biomass per hectare in Sweden. Total energy use for pulpwood production and supply are in a similar order of magnitude, up to 395 MJ and 370 MJ/m<sup>3</sup> solid under bark in Spain and Sweden, respectively. Field operations, such as silviculture and logging, are more energy-intensive in the Spanish case study. However, secondary hauling of pulpwood to pulp mill requires more energy in the Swedish case study. These important differences are related to different forest management practices as well as to pulpwood supply to the pulp mill. The eventual imports of pulpwood, application of pesticides, thinning step or final felling considerably affects energy requirements, which are reflected on the environmental results.

**Discussion** Although differences between both case studies were observed, several stages were investigated: wood delivery to the pulp mill by road, harvesting and forwarding, contribute considerably to acidification, eutrophication and global warming potential in both cases. The type of wood, the machines used in forest operations (mechanised or motor-manual), the use of fossil fuels and the amount of wood produced influence the results. These differences must be kept in mind in comparative studies between such different countries.

**Conclusions** The results obtained in this work allow one to forecast the importance of forest operations in LCA of forest products (in this case, wood pulp) and the influence of energy use in the results. Special attention has been paid in the inventory analysis stage for both case studies. It is

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possible to gain a better environmental performance in both case studies if alternative practices are considered, mainly focused on site preparation and stand tending in the Spanish system and on pulpwood supply in the Swedish one.

**Recommendations and perspectives** This study provides useful information that can assist forest-based industries in the aim of increasing their sustainability. Future work will focus on the study of several transport alternatives of pulpwood supply including railway, road and ship. In addition, pulpwood processing in Spanish and Swedish paper pulp mills considered to be representative of the “state of art” will be carried out in order to get a complete picture of this kind of forest-based industry. In addition, the use of biofuels (such as forest biomass) instead of fossil fuels and CO<sub>2</sub> uptake of wood via photosynthesis will be carried out in order to have a complete perspective of forest ecosystems.

**Keywords** Energy use · Environmental impacts · *Eucalyptus globulus* · Forest operations · Pulpwood · Renewable resources · Spain · Sweden

## 1 Background, aim and scope

The forest sector in EU is characterised by a great diversity of forest types, extent of forest cover, ownership structure and socio-economic conditions. In total, forests and other wooded land occupy around 160 million ha or 35% of the EU's land area. Moreover, as a result of forestation programmes, forest cover in the EU is increasing. EU is one of the largest producers, traders and consumers of forest products in the world (European Commission 2006). The annual production value of forest sector is about € 356 billion in 2001 and employs approximately 3.4 million people (European Commission 2007).

Nowadays, wood constitutes the main raw material of virgin paper pulp in developed countries (Sigoillot et al. 2005) and pulp manufacturing is the first non-food industrial utilisation of plant biomass (Gutierrez et al. 2001). The pulp and paper industry in Europe, with a 2003 capacity greater than 41 million tonnes/year of pulp and 95 million tonnes/year of paper- and cellulose-based products, occupies the second position in world production of pulp and paper.

The European industry consists of more than 1,000 paper mills and 220 pulp mills. Germany is the largest paper producer followed by Finland, Sweden and France. Regarding pulp production, Finland and Sweden are the main pulp-producing countries (European Commission 2007). The forest sector has a considerable weight in the national economy, which is important regarding exports and work perspectives (European Commission 2007). The target of the Swedish pulp and paper industry is to create

globally competitive companies. Currently, there are around 30 large paper pulp mills and their total annual paper pulp production amounts to 12 million tons (Reciclapapel 2007; Skogsstatistisk Årsbok 2007). Roughly, 44% of the total wood harvested in Swedish forests is delivered to this sector. Considerable amounts of wood are also imported, mainly from the Baltic countries and Russia (Swedish Forest Agency 2008). Spain stands for a remarkable pulp production with more than 130 mills, some of them being representative of up-to-date industrial mills. Annual pulp production is on the order of 2 million tons and consumes about 6 million m<sup>3</sup> of wood from fast-growth species such as *Eucalyptus globulus* and *Pinus radiata* (Aspapel 2007). According to this data, forest sector plays an emerging important role in the Iberian Peninsula socio-economic development.

During forest management not only good quality stem wood is produced but also low-quality wood, branches, resins and bark. In addition, forests provide other environmental benefits such as soil and water protection and they favour proliferation of non-wood products such as medical plants, mushrooms and berries. Furthermore, renewable forest-based fuels are considered carbon dioxide neutral. However, mechanised and motor-manual operations carried out in forest management practices require large amounts of fossil fuels, which imply emission of pollutants to the environment.

The increasing environmental awareness of consumers, evident in global certification schemes, requires increased knowledge concerning the environmental impacts of forest practices.

The countries considered: Spain and Sweden, constitute two case studies with significant differences such as type of wood processed, degree of mechanisation in logging operations and fossil fuel requirement, which will have influence on their associated environmental impacts.

Life cycle assessment (LCA) is a methodology that aims to analyse products, processes and/or services from an environmental point of view (Baumann and Tillman 2004). LCA of forestry and forest-based products is a relatively new and developing field of science which is already seen as an important tool to evaluate the environmental impact of forestry activities and forest products. This tool could help to improve wood production as well as to identify processes or stages in the wood chain with a high environmental impact or highlight areas where environmental information is unknown. Up to date, LCA has already been considered to evaluate the environmental impact of wood-related products (Rex and Baumann 2007). Recent publications on LCA have studied forest-based products such as paper and pulp (Dias et al. 2007a; González-García et al. 2009a), boards (Rivela et al. 2006a; Rivela et al. 2007; González-García et al. 2009b), furniture and/or wood floor coverings (Nebel et al. 2006; Werner and Richter 2007) as well as the use of wood wastes in ephemeral architecture

(Rivela et al. 2006b). It is important to take into account that forestry can be challenging in LCA studies due to the different scales of the stand management in young stands compared to forest operations in mature stands (such as logging or secondary hauling). Moreover, several environmental impacts of wood extraction appear gradually. Therefore, this process would be studied during time-scales extended for decades without focusing on events at specific sites and times (Lindholm 2006).

However, some of these studies have not analysed in detail the raw material production or they have turned to databases in their analysis. Therefore, its evaluation is needed since the impact of different forestry systems and transport of round wood is not commonly known to LCA practitioners and, in some cases, could be a hot spot due to, for example, eutrophying related emissions. Only some papers can be found concerning environmental effects of forest operations, almost all of which are situated in Scandinavian countries (Aldentun 2002; Berg and Karjalainen 2003; Berg and Lindholm 2005; Lindholm and Berg, 2005a, 2005b; White et al. 2005; Michelsen 2007; Michelsen et al. 2008) and Portugal (Dias et al. 2007b). LCA has also been used by some authors to evaluate the material consumption in some forest operations (mainly logging) due to spare-part use by harvesters and forwarders (Athanasiadis 2000; Athanasiadis et al. 2000) or to analyse the Swedish road transport (Eriksson et al. 1996).

So far, no comparative LCA study has been carried out for Swedish and Spanish pulpwood production. This paper compares energy use in Swedish and Spanish forest operations that leads to pulpwood production. The limitations of each case study were identified and improvement alternatives were proposed. This study comprised the most important tree species used in pulp mills in both countries: *E. globulus* in the Spanish case study and Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) in the Swedish one.

## 2 Goal and scope

### 2.1 Objectives

LCA is a methodology for the comprehensive assessment of the impact that a product has on the environment throughout the life span of the product (from extraction of raw materials to disposal of the product at the end of its use). In the forest sector, LCA may not only allow one to propose improvement actions for specific areas in the forest chain, but also to demonstrate environmentally satisfactory applications of wood for industry and consumer markets (Karjalainen et al. 2001; Werner and Nebel 2007). Keeping in mind that the forest industry mainly uses a renewable raw material, with a potential such as carbon storage, this

sector would also have other environmental benefits due to low fossil fuel use, low emissions to air, water and soil.

This paper compares two forest case studies (one in Spain and the other in Sweden) of pulpwood production and wood supply to Spanish and Swedish pulp mills, respectively. The basic statement was that a large proportion of the environmental load by forestry activities is derived from the use of machinery powered by fossil fuels (diesel, petrol and lubricants). Concerning pulpwood production, three forest plantations considered representative of the “state of the art” were selected and analysed in detail: one Spanish stand (located in NW Spain) and two Swedish stands (placed in Central and Southern Sweden). The main objectives of this study were:

1. Identification of the forest operations which take place in both forest case studies with the corresponding energy and/or raw material requirements
2. Identify the most intensive processes in terms of energy use, which represent the highest contributions to the environmental impact categories analysed in both case studies,
3. Proposal of some improvement alternatives

### 2.2 Functional unit

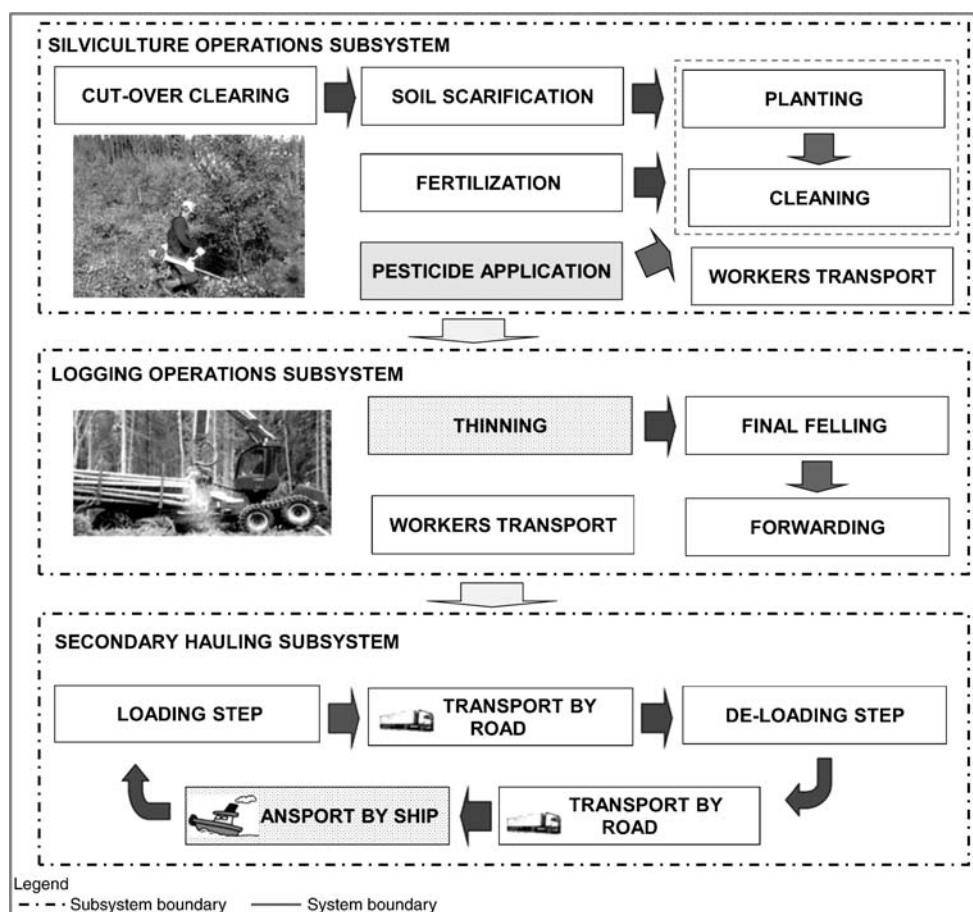
The function of the forest systems under study is to produce and supply pulpwood which is the main fibre raw material used in pulp mills and therefore, the functional unit was defined as “1 m<sup>3</sup> of industrial pulpwood solid under bark (m<sup>3</sup> s.u.b.)” delivered to pulp mill. The selection of the functional unit seems to be in agreement with other forest-related LCA studies (Berg and Karjalainen 2003; Berg and Lindholm 2005; Schweinle 2007; Michelsen et al. 2008; González-García et al. 2009c, d), where a volume-based functional unit was also selected. Moisture content in both types of wood is 40% and densities of the Spanish and Swedish wood are 549 and 399 kg/m<sup>3</sup>, respectively (Berg and Lindholm 2005).

### 2.3 Description of forest systems under study

The study includes the Spanish and Swedish forest systems for the production of pulpwood (hard and softwood, respectively) from silviculture operations to wood delivery to pulp mill gate. Forest management practices chain is divided in three main subsystems: silviculture operations, logging operations and secondary hauling. Description of the systems evaluated is presented in Fig. 1.

*Subsystem of silviculture operations* The establishment of forest plantation starts with site preparation, which includes eradication of unwanted vegetation (cut-over clearing) in

**Fig. 1** Subsystems included in the Spanish/Swedish case study: process chain. *White boxes* are common for both processes, *spotted boxes* occur at the Swedish case study and *striped boxes* at Spanish case study



order to facilitate the regeneration treatment and soil scarification to break up the forest ground as preparation for regeneration. Soil preparation in Sweden is mainly performed by mechanised, propelled units, such as rotary cultivators, disc trenchers and mounds with a forwarder used as base machine (Mattsson and Bergsten 2003; Johansson et al. 2007). The cut-over clearing is either made motor-manually or mechanised as an integrated part of soil preparation. In the Spanish case study, both processes are completely mechanised and disc trenchers and rippers connected to tractors are commonly used.

After scarification, regeneration takes place and in both case studies, artificial regeneration (that is, the creation of a new stand by sowing or planting) is considered. Spanish and Swedish regeneration is performed by means of manual planting using with planting pipe. However, transportation of seedlings and items for planting is mechanised. After planting, agro-chemicals are applied. Fertilisation and pesticide application (the latter application only in the Spanish case study) is necessary to reduce mortality of the desired tree species and to enhance wood growth. NPK-based fertilisers and pesticides in the Spanish system and only N-based fertilisers in Central Sweden are used. In the case of Southern Sweden, there is no application of any fertiliser because soils are nitrogen rich. The agro-chemical

application in Spain is manual in the case of fertiliser (only the first application) and mechanised in pesticide application. In Central Sweden, the process of fertilising is mechanised with a helicopter.

Along the stand treatment, some mechanised practices have to be carried out such as cleaning, fertilisation and/or pesticide application (the latter application only in the Spanish system). Removal of unwanted vegetation in young stands is necessary to regulate tree species, composition, spatial distribution, growth and quality. Currently, cleaning is motor-manual (brush saw) and mechanised in the Swedish and Spanish case studies, respectively.

*Subsystem of logging operations* Thinning, (final) felling and extraction of wood are included in logging operations. There are significant differences between the Spanish and Swedish case studies. In the Spanish logging subsystem, no thinning is performed, trees are felled with a chainsaw (motor-manual) and a wheel-harvester is used to fell the remaining trees and, finally, transfer of wood to the roadside is carried out by forwarders. In the Swedish logging subsystem, roughly 40% of stand is thinning (immature stands) in order to improve future stands development and to guarantee forest income (Eriksson 2006). The remaining 60% is final felling. Both operations are carried out by means of a single-grip

harvester. A standard Swedish stand is normally thinned two to four times during its growth cycle (Aldentun 2002). The extraction stage normally uses a forwarder.

**Subsystem of secondary hauling** This subsystem consists of transport of harvested wood from the forest landing to the pulp mill gate. There are huge differences between both case studies. In the Spanish case study, transport is only carried out by road vehicles and in the Swedish case, road and maritime transportation are combined since not only Swedish wood is used but also wood from Baltic countries (25% of total). Wood lorries weighing 40 and 60 tons and an average load factor of 50% and 57% are used in the Spanish and Swedish case studies, respectively. The average distance by road from forest landing to the pulp mill gate in the Spanish case study is 90 km and in the Swedish, 100 km. Lorries considered are not equipped with loaders and are served by independent loaders. In maritime transport (only in the Swedish case), the ships considered have the possibility to carry between 3,000 and 5,000 m<sup>3</sup> of pulpwood with bark.

## 2.4 System boundaries

### 2.4.1 Spanish case study (SP)

The Spanish case study is focused on eucalyptus wood production since this is the main raw material for high quality Kraft pulps (González-García et al. 2009a). Forest operations considered in the study are those carried out in a Spanish *E. globulus* plantation representative of ‘state of the art’ during one whole year (season 2006–2007). This plantation is located in NW Spain (Fig. 2), its plot area is 40 ha and belongs to a Spanish large forest company. Interviews as well as visits to the company and informal conversations were carried out in order to gather inventory

data. In addition, this data was completed with company reports and bibliographic resources (ENCE, 2008).

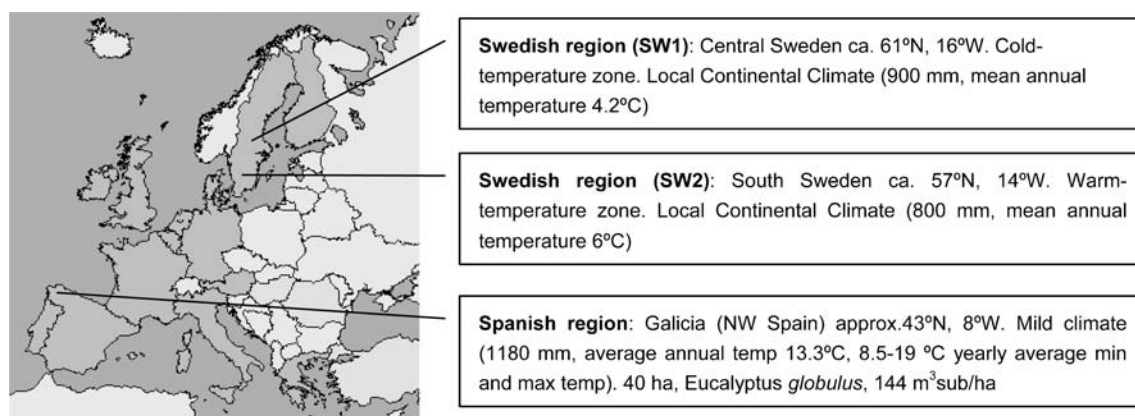
System boundaries (see Fig. 1) cover forest operations (silviculture and logging operations) and secondary hauling (from forest landing to pulp mill gate), which includes loading and de-loading steps. Forest workers transportation to working sites was also included in the system boundaries.

Energy requirements related to each forest operation, as well as fertiliser and pesticide use, production and transport were taken into account. In addition, the system included not only field operations but also impacts related to extraction and production of energy carriers as well as production and transportation of system inputs (inorganic fertilisers and synthetic pesticides).

Production of capital goods (machinery, buildings and roads), transport of energy carriers and ancillary materials from the industry production to the forest management region were not included within system boundaries. The assimilation of CO<sub>2</sub> in biomass during tree growth as well as impacts on biodiversity (operations impact and possible contribution to species depletion) was not considered.

### 2.4.2 Swedish case study (SW)

The Swedish case study will focus on the production of Norway spruce and Scots pine, because these are the main raw materials for the manufacturing of wood pulp in the Swedish mill under study (80% and 20%, respectively) as well as also in the Scandinavian countries (Swedish Forest Agency 2008). Two Swedish Norway Spruce and Scots Pine stands considered representative of the ‘state of art’ were selected to study the Swedish wood production process in detail. Inventory data from the Swedish case study was collected by means of surveys from forest management regions in Central (SW1) and Southern (SW2) Sweden (see Fig. 2), since these are the origins of 75% of total round



**Fig. 2** Characteristics of the forest stands considered in the study to analyse pulpwood production: Central Sweden (SW1), South Sweden (SW2), and NW Spain

softwood processed in the Swedish pulp industry under study (45% and 30% of total, respectively). Information regarding wood origin processed in the pulp mill and forest practices was supplied by Swedish pulp mill workers by means of personal communications, surveys and visits to the pulp mill. The remaining 25% comes from Baltic countries (58% from Latvia, 23% from Estonia and 19% from Lithuania) and it was assumed that Swedish forest management practices are also representative of operations in the Baltic countries. According to the Final Report compiled by the FO5 Working Group given in Baltic 21 Forest Sector Meetings (Baltic 21 FO 5-project, 2007) and based on the knowledge regarding operating conditions and machine systems currently in use in Baltic countries, it has been estimated that a total energy use in stand establishment, tending and logging is up to 30% higher in the worst case. If an increase in energy use of 30% is considered in logging and silviculture operations all together, the total energy use would increase by only 3% (in the worst case) with minimum effect over the environmental impact categories under study. As presented for the Spanish case study, the Swedish study covers up to (and including) all the forest activities that take place in forest from silviculture operations to harvesting and final transport of round wood (softwood) from landing to pulp mill gate (see Fig. 1).

## 2.5 Data quality

As mentioned earlier, field data in both case studies was gathered by means of company reports, interviews, visits to companies, informal conversations as well as surveys of the forest operations. In addition, this data was completed with bibliographic resources. Life cycle inventory (LCI) data for fuels (petrol and diesel) used in the study comes from Frischknecht et al. (1996) and lubricants were assumed to have the same LCI as petrol according to Uppenberg et al. (2001). Inventory data related to the production of fertilisers used in the systems (NPK in Spanish case study and ammonium nitrate with dolomite and 27% of Nitrogen for Swedish case) came from Nemecek et al. (2004) and Davis and Haglund (1999). The use of agro-chemicals is an important source of nutrient-related emissions with an important contribution to global warming, acidification and eutrophication (Charles et al. 2006). It is necessary to develop an entire mineral balance for each particular case study to determine emissions from fertilisers since emission rates are variable due to the influence of soil type, climatic and agricultural conditions. However, an entire mineral balance was not undertaken due to the lack of data and the calculation of nutrient-related emissions (ammonia, nitrate, nitrogen, nitrous and nitrogen oxides and methane) was obtained by means of emission factors proposed by several authors (Audsley et al. 1997; Brentrup et al. 2000; Arrouays

et al. 2002; EMEP/CORINAIR 2006). Data for atmospheric deposition in Galician (NW Spain) and Swedish soils were taken from Rodríguez and Macías (2006) and Skogsstatistisk Årsbok (2007), respectively. In addition, it was necessary to determine the total biomass (stem, bark, living branches, dead branches, needles, stump and roots) to calculate the amount of total nitrogen retained and complete the nitrogen-based balance. This value was obtained according to Lehtonen et al. (2004) and Praktisk Skogshandbook (1994). Simultaneously, forest ecosystems act as filters, removing most of the atmospheric deposited nitrogen. Regarding phosphorous loss from field, its estimation strongly depends on local conditions as well as the type of farming system. Some authors have estimated P loss between 0.01 and 1.8 kg/ha (Audsley et al. 1997; Välimaa and Stadig 1998; Djodjic et al. 2004). In this study, it was considered an emission factor to surface water of 0.024 kg P/kg P applied (Audsley et al. 1997).

The spread of nitrogen-based fertiliser (mainly ammonium nitrate) in the Swedish central region is carried out by helicopter. In Southern Sweden, there is no application of fertilisers because soils are nitrogen rich. In addition, it must be stated that phosphorous and potassium-based fertilisers were not applied due to the fact that Swedish soils are rich in these nutrients (Djodjic et al. 2004). Emission factors associated with helicopters were taken from Johansson and Basander (2003) and the LFV Group (2005).

Plant protection substances are applied in order to control organisms to improve productivity of forest systems. A part of these substances cause an impact upon terrestrial and aquatic ecosystems as well as humans via wind drift, evaporation, leaching or surface run-off (Brentrup et al. 2004). Emissions of synthetic pesticides to air, surface water, groundwater and soil were estimated according to the method proposed by Hauschild (2000). Pesticide application is not a common practice in Swedish forestry and, for this reason, it was not considered within the system boundaries. However, pesticide application process takes place in the Spanish case study and Roundup® (glyphosate 36%) is the pesticide applied. It is one of the most commonly used herbicides worldwide because of its efficient weed control and negligible persistence in the environment (Amorós et al. 2007). Inventory data for pesticide production (organophosphorous compound) came from Audsley et al. (1997), Ahlgren (2003) and Nemecek et al. (2004).

Representative factor emissions for the Spanish forest machines (CO, NO<sub>x</sub>, HC) were approximated to Swedish forest and agricultural machines and according to Hansson et al. (1998). Other emission factors for the machines (CO<sub>2</sub>, VOC, CH<sub>4</sub>, N<sub>2</sub>O, particulates) were taken from Uppenberg et al. (2001). In the case of motor-manual machinery, factor emissions came from Holmgren (2000) and Naturvårdsverket (2002). Regarding the emission factors associated with heavy

lorries (used in secondary transport), they were taken from Frees and Weidema (1998) and The Network for Transport and Environment (NTM 2007a) for the Spanish and Swedish case studies, respectively. Emission factors associated with transport by ship were taken from Frees and Weidema (1998) and the Network for Transport and the Environment (2007b). It is important to show that the sulphur maximum legal content in Spanish and Swedish fuel is 2,000 and 2 ppm, respectively (NTM 2007a; BOE 2006) and these values were taken into account for all forest processes.

Independent loaders were used in the secondary transport system since lorries with no crane were considered in the systems under study. Energy requirements in the loading and unloading steps came from Forsberg (2002).

### 3 Life cycle inventory analysis

Energy use was studied for all forest operations. Data related to the effective work time (h/ha) and fossil fuels consumption (L/h) in each forest process were taken into account: diesel consumption by harvesters, forwarders, tractors, lorries, ships and helicopters; petrol consumption by chain saws and brush saws; lubricants and engine oils used. These values expressed in MJ/m<sup>3</sup> s.u.b. are reported in Table 1 and Table 2 for Spanish (SP) and Swedish (SW) systems. All wood processed in SP comes from Spanish eucalyptus plantations managed under similar conditions considered in this paper and wood transport from landing to pulp mill gate is only by road transport. However, in the SW, 75% of total pulpwood processed is Swedish and the remaining 25% is imported from Baltic countries, which breaks down to 58% from Latvia, 23% from Estonia and 19% from Lithuania. As mentioned before, no large differences between forest management in Sweden and the Baltic countries were assumed. Therefore, field operations (silviculture and logging subsystems) were assumed only under Swedish conditions in ratios of 40% from Southern Sweden and 60% from Central Sweden.

For imported wood, its delivery was combined by road and boat transport. Due to the location of the pulp mill, this alternative was also considered when pulpwood comes from Southern Sweden (30% of total wood processed in the factory). The remaining 45% is from Central Sweden and only road transport is considered.

### 4 Environmental analysis

In this study, the impact assessment was performed according to the Swedish Environmental Management Council (2000), and, in particular, the impact categories commonly used in forest and agricultural LCAs: global

**Table 1** Energy use (MJ) per functional unit (1 m<sup>3</sup> solid under bark) for all forest operations carried out during site preparation, stand tending and logging

Subsystem	Case studies			
	SP	SW1	SW2	SW
<b>Silviculture operations</b>				
Cut-over clearing	9.3	0.05	0.05	0.05
Soil scarification	21.0	2.9	2.1	2.6
Planting	— <sup>a</sup>	1.2	0.59	0.94
1st Fertilisation	— <sup>a</sup>	1.2	— <sup>b</sup>	0.73
1st Pesticide application	2.8	— <sup>b</sup>	— <sup>b</sup>	— <sup>b</sup>
Cleaning	27.9	1.2	0.36	0.87
Fertilisation <sup>c</sup>	11.2	—	—	—
Pesticide application <sup>c</sup>	—	—	—	—
Fertilisers production	41.4	6.3	— <sup>b</sup>	6.3
Pesticides production	0.11	— <sup>b</sup>	— <sup>b</sup>	— <sup>b</sup>
Workers transportation	2.5	— <sup>d</sup>	— <sup>d</sup>	— <sup>d</sup>
Total energy use	116.2	11.7	3.1	11.5
<b>Logging operations</b>				
Thinning	— <sup>e</sup>	60.5	39.8	52.2
Final Felling	14.0 <sup>f</sup> +69.9 <sup>g</sup>	30.0	26.6	28.6
Extraction	69.9	54.3	55.7	54.9
Workers transportation	1.4	— <sup>d</sup>	— <sup>d</sup>	— <sup>d</sup>
Total energy use	155.1	114.8	122.1	135.7

SP Spanish Case study (plantations: 100% NW Spain), SW1 forest plantation placed in Central Sweden, SW2 forest plantation placed in South Sweden, SW Swedish Case study (plantations: 60% SW1+40% SW2)

<sup>a</sup> There is no energy use since this step is completely manual

<sup>b</sup> This process does not take place

<sup>c</sup> These activities only take place in eucalyptus stands treatment

<sup>d</sup> Energy use is included in energy requirements of each process

<sup>e</sup> This operation is exclusive to Spruce and Pine stands

<sup>f</sup> Felling with a chain saw

<sup>g</sup> Final felling with a harvester

warming (GW), acidification (AC), eutrophication (EP) and photochemical oxidant formation (PO), were analysed. Only the phases of classification and characterisation were studied, as this represents the most objective approach since it includes no interpretation of values when judging the importance of different impact categories. Characterisation factors for GW were adapted from IPCC (2007). The LCA software SimaPro 7.10 developed by PRé Consultants (2008) was used to perform the impact assessment stage. The results for the characterisation step are shown in Table 3.

Other environmental aspects could be included such as land use and biodiversity. However, it was not possible to find a common method with equivalent data quality that can reflect the impacts in a comparable way. The issue is

**Table 2** Energy requirements per functional unit and parameters used for secondary hauling subsystem in Spanish (SP) and Swedish (SW) case studies

Secondary hauling subsystem	Case studies			
	SP	SW		
Transport system		Baltic countries (25%)	South Sweden (30%)	Central Sweden (45%)
Lorry				
Max. weight	40 t	40 t	60 t	60 t
Cargo capacity	25 t	25 t	40 t	40 t
Load factor <sup>a</sup>	50%	57%	57%	50%
Distance	90 km	100 km	100 km	100 km
Empty fuel consumption	0.35 L/km	0.45 L/km	0.45 L/km	0.45 L/km
Full fuel consumption	0.60 L/km	0.62 L/km	0.62 L/km	0.62 L/km
Ship				
Load	— <sup>b</sup>	3200 m <sup>3</sup>	3200 m <sup>3</sup>	— <sup>b</sup>
Distance	— <sup>b</sup>	414 <sup>c</sup> nm	368 <sup>d</sup> nm	— <sup>b</sup>
Fuel consumption	— <sup>b</sup>	0.01 L/t·km	0.01 L/t·km	— <sup>b</sup>
Total energy use <sup>e</sup>	124 MJ/m <sup>3</sup> s.u.b.	94 MJ/m <sup>3</sup> s.u.b. 223 MJ/m <sup>3</sup> s.u.b.	89 MJ/m <sup>3</sup> s.u.b.	40 MJ/m <sup>3</sup> s.u.b.

<sup>a</sup> Distance driven with a full load (100%) per round trip<sup>b</sup> There is not transport by ship in this case study<sup>c</sup> Transport from Baltic countries: 428 nm from Riga (58%), 461 nm from Klaipeda (19%) and 340 nm from Pernu (23%)<sup>d</sup> From Oskarshamn shipping port to pulp mill's shipping port<sup>e</sup> Total energy use entailing transportation with full load in one way and coming back empty on the return journey. Loading (158 MJ/lorry) and unloading (123 MJ/lorry) steps are also included.

relevant but tool and data were not available. A closely related subject is also the content of soil organic matter, which is different in the forestry soils considered in this study (Jones et al. 2004). Nevertheless, we cannot describe how the processes used for forest management could influence the different locations. Moreover, there is no standard methodology for including the impact on biodiversity from land use activities in LCA (Milà i Canals et al. 2007).

**Table 3** Results of characterisation stage as well as total energy use related to the functional unit of 1 m<sup>3</sup> solid under bark delivered to Spanish and Swedish pulp mills

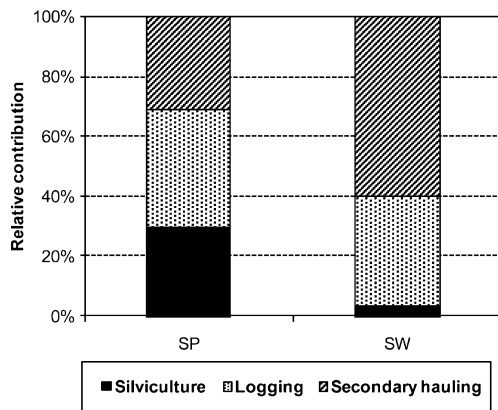
Category	Unit	Case studies	
		SP	SW
GW	kg GWP100 eq	35.5	36.1
EP	g O <sub>2</sub> eq	5590	2610
AC	mol H <sup>+</sup> eq	11.4	10.2
PO	g C <sub>2</sub> H <sub>2</sub> eq	53.2	40.8
Energy use	MJ	395.1	370.2

#### 4.1 Non-renewable energy use

The Spanish case study of wood production and supply to a pulp mill requires lightly more energy than the Swedish case study, up to 7% more. The energy use required to produce and supply 1 m<sup>3</sup> s.u.b. of pulpwood was 395 MJ in Spain and 370 MJ in Sweden. This included all forest processes from silviculture operations to its delivery to a pulp mill. In both case studies, diesel is the main energy used, even though petrol and lubricant oils were also used. Figure 3 shows the contributions of each subsystem to the total energy use. The more energy-intensive subsystems are logging operations in SP (mainly due to harvester and forwarder) and secondary hauling in SW (due to maritime domestic and international transport).

#### 4.2 Global warming potential (GW)

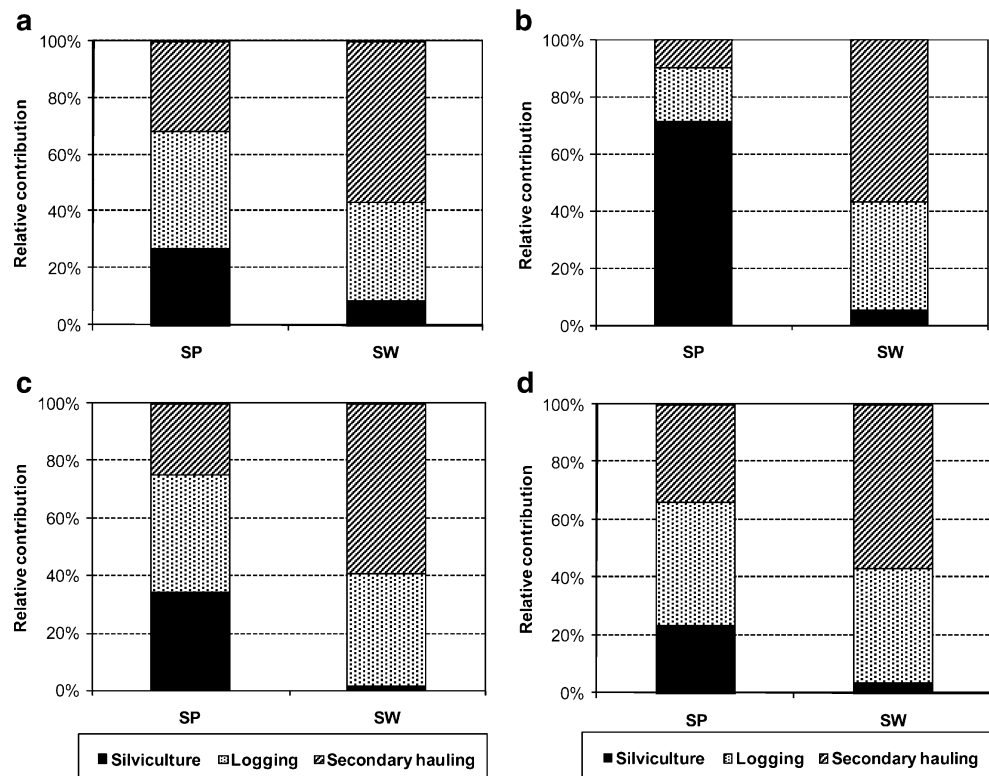
Emissions of CO<sub>2</sub> equivalents emitted per m<sup>3</sup> s.u.b. are considerably higher than other values reported (Schwaiger and Zimmer 2001; Berg and Lindholm 2005; Michelsen et al. 2008). Contributions of the secondary hauling subsystem cannot be compared with these studies as they depend strongly on the origin of the pulpwood processed in a



**Fig. 3** Contributions (in %) of each subsystem to energy use in Spanish (SP) and Swedish (SW) case studies

specific pulp mill and large differences were identified. The mechanised degree and effective work time as well as the nature of the stands influence the results. Figure 4a shows the relative contributions to GW of subsystems in which forest operations were divided. Regarding the main substances contributing to GW, CO<sub>2</sub> fossil emissions are those which are mainly responsible (more than 90% in both case studies), followed by N<sub>2</sub>O and CH<sub>4</sub> emissions. These figures agree with the results reported by other authors (Karjalainen and Asikainen 1996; Berg and Karjalainen 2003; Berg and Lindholm 2005).

**Fig. 4** Analysis of contributions per system in impact categories under study: **a** GW, **b** EP, **c** AC, **d** PO



### 4.3 Eutrophication (EP)

Eutrophication is one of the most important categories in agricultural systems due to the eutrophication emissions associated with fertiliser application (Audsley et al. 1997; Milá i Canals 2006). Remarkable differences were found when comparing the two case studies. In the Spanish case study, the application of P-based fertilisers contributes considerably to this impact category being responsible for 54% of the total eutrophying emissions. In the Swedish case study, only low amounts of N-based fertiliser are applied; therefore, 95% of total emissions are NO<sub>x</sub> generated in logging and secondary hauling due to fossil fuel combustion. Figure 4b shows the relative contributions per subsystem to this category.

### 4.4 Acidification (AC)

In SW, the secondary hauling subsystem is the most important contributor to AP and figures approximately 60%, followed by logging and silviculture operations according to Fig. 4c. This result fits in with other studies under Scandinavian conditions (Berg and Karjalainen 2003; Berg and Lindholm 2005). Emissions of sulphur (9%) and nitrogen oxides (88%) presented the greatest contributions to this impact category and they are derived from fossil fuel combustion. The main processes are: wood

supply by ship (40%), by lorry (18%), forwarding stage (16%) and thinning stage (15%).

Regarding SP, the logging subsystem is mainly responsible followed closely by the silviculture subsystem due to the use of highly mechanised operations. Secondary hauling had the smallest contribution (see Fig. 4c). The harvesting stage, with a harvester and forwarding stage are responsible for 21% and 20%, respectively. Fertilising and cleaning stages contribute to 16% and 11%, respectively. The main contributors for energy-related emissions are  $\text{NO}_x$  and  $\text{SO}_x$ . Both compounds originated from fuel combustion, although  $\text{NO}_x$  is generated in the combustion processes in engines and  $\text{SO}_x$  is released from sulphur-containing fossil fuels, representing 68% and 18%, respectively.

#### 4.5 Photochemical oxidant formation (PO)

The logging operations subsystem is the most important contributor in this impact category in the Spanish case study. Its contribution adds up to roughly 43% of total, followed by secondary hauling and Silviculture operations (Fig. 4d). Hydrocarbon emissions (specifically, NMVOC and VOC) formed during the incomplete combustion of fossil fuels are responsible for almost 100% of contributions to this environmental category. In the Swedish case study, secondary hauling is responsible for more than 60% of photo-oxidant emissions, followed by logging and silviculture. The most important process is pulpwood delivery by ship and it amounts to 30%. Similar to SP, hydrocarbon emissions (NMVOC and VOC) represent approximately 100%.

## 5 Discussion

LCA allows one to point out areas in the forest-wood chain which need improvements and to demonstrate environmentally good applications of wood for industry and consumer markets (Karjalainen et al. 2001; Werner and Nebel 2007). The availability and quality of inventory data in an LCA study in the forestry sector will depend on management and landowner structure as well as on the country under study. In the case of Nordic countries and mainly Sweden, useful data of good quality of the different forest operations is available. The main difference to other related studies (Karjalainen and Asikainen 1996) where general data from statistics was considered, this study relied mostly on real field data.

There are large differences between the Spanish and Swedish field and forest operations (silviculture and logging subsystems) and the procedure of wood supply to a pulp mill (secondary hauling subsystem). Currently, 16 million  $\text{m}^3$  of roundwood are annually produced in Spain compared to nearly 100 million  $\text{m}^3$  of roundwood produced in Sweden (Skogsstatistisk Årsbok 2007). Industrial wood processed

in Sweden is mainly from coniferous species (roughly 95% of the total). However, in Spain, it is around 50% from coniferous species and 50% from non-coniferous species although from the wood pulp production point of view, more than 70% of wood processed is eucalyptus (non-coniferous species; Gutierrez et al. 2001; Skogsstatistisk Årsbok 2007).

The productivity of forests, the mechanised degree of forest operations, the origin of wood processed as well as the kind of downstream user seem to be the main influence in the environmental burdens. The results from this environmental study indicate that forest operations in Spain use more energy per cubic metre solid under bark than in Sweden (up to 7% higher). More than 69% of non-renewable fuel consumption in the Spanish case study takes place in field operations (silviculture and logging). However, in the Swedish case, this value adds up to 40% approximately (see Tables 1 and 2). Wood transport between forest landing and pulp mill gate (secondary hauling subsystem) was reported by several authors as one of the most problematic steps (or hot spots; Karjalainen and Asikainen 1996; Karjalainen et al., 2001; Berg and Karjalainen 2003; Berg and Lindholm 2005, 2005a, b). Therefore, improvement opportunities in both case studies will be suggested below.

#### 5.1 Improvement opportunities to the silviculture system

Silviculture operations presented a small contribution in all the impact categories in SW and in two of the four impact categories in SP. Silviculture operations are those which are mainly responsible for EP (in the Spanish case study) due to phosphorous-based fertiliser application. Total phosphorous leaching takes place and contributes to eutrophication of freshwater systems. Only N-based fertilisers are applied in Swedish soils as they are rich in P and K. In Spain, in contrast, it is necessary to apply NPK-based fertilisers. Therefore, a recommendation could be related to the optimum dosage of fertiliser or the best moment of application (climate conditions) in order to reduce nutrient loss.

There is no pesticide application in Swedish industrial wood stands. Pesticide production requires high energy use (up to 200 MJ/kg active substances) and pesticide-related emissions are generated (Audsley et al. 1997; Ahlgren 2003; Nemecek et al. 2004). However, their contribution to all impact categories is negligible.

Energy use by the silviculture system is roughly 90% higher in SP than SW due to highly mechanised operations and chemical use. Larger engines in cleaning and soil scarification steps are used in Spain, usually up to three cleaning steps are carried out during the stand treatment by means of a crane-tip connected to a tractor or forwarder and the entire stand is scarified. In Sweden, on the other hand, cleaning is carried out almost exclusively using motor-

manual methods with a brush saw. Introduction of furrowers in soil scarification stage and mowers in cleaning stage would reduce energy use and fossil fuel emissions.

Another interesting alternative is the use of biomass-derived fuels (for example, wood waste) in mechanised silviculture operations instead of fossil fuels (Ahlvik and Brandberg 2001).

### 5.2 Improvement alternatives to logging system

SP is a more intensive energy consumer than SW (up to 13%) and other Scandinavian countries (Michelsen et al. 2008). There are important differences between both case studies. Thinning, final felling and forwarding constitute the logging operations in Sweden. However, in the Spanish case study, there are no thinning operations due to shorter periods of growing, but plantations need higher execution frequency (e.g. cleaning steps).

There are two different processes in this forest management stage: motor-manual cutting (using chain saws) and mechanised cutting (using harvesters). In the countries of Northern Europe, it is very common to use harvesters. However, in SP, both alternatives are used. Regarding the productivity, it depends on the volume of wood processed which is higher in the mechanised processes. Spanish effective work time (h/ha) is considerably high compared with other results reported (Markewitz 2006; Dias et al. 2007b). Therefore, special attention must be paid to all these processes.

Nowadays, studies are underway to develop a single machine for harvesting and forwarding work in order to reduce fuel consumption per cubic metre of wood harvested as well as to introduce new technologies in this forest stage, such as electric motors (electric hybrid forwarders) or fuel cells. Some authors have reported energy reduction of 20–50% in fuel consumption per cubic metre of harvested wood in comparative studies between conventional forwarder and hybrid forwarder (Löfroth et al. 2007).

### 5.3 Improvement alternatives to secondary hauling

Secondary hauling is considered the main hot spot in European forest operations and several studies have led to this conclusion (Karjalainen and Asikainen 1996; Karjalainen et al. 2001; Berg and Karjalainen 2003; Berg and Lindholm 2005, 2005a, b). There are several ways of decreasing energy demands in the secondary road transport, such as reducing transport distance, adjusting load factors, designing better route-planning systems, improving roads (curve geometry and surfaces), adopting more fuel-efficient driving techniques and using the best available transport carriers. In addition, conscious wood drivers would allow decreasing energy use by 10% (Forsberg and Löfroth 2002).

Weight and payload of freight lorries are regulated in European countries and there are wide variations. In the case of Spain and the Baltic countries, wood lorries are allowed a total gross weight of 40 tons (roughly 25 tons of payload). However, in Sweden, the maximum load for a wood rig is 60 tons. These differences have influenced fuel consumption per m<sup>3</sup>s.u.b. If Swedish conditions could be applied to the Spanish, reductions up to 40% of energy used in this system could be reached.

In SW, wood transport by road and ship was considered due to the adequate location of the pulp mill. However, transport by railway was not taken into account being actually one of the most important transport alternatives for goods (including wood) between European countries and the second most important for domestic transport of roundwood in Sweden (after road transport) (Skogsstatistisk Årsbok 2007). The Swedish railway network comprises roughly 12,000 km and, in Southern Sweden, it enables transport in all directions. Usually, transport by train is used instead of lorries for long-distance roundwood supply (the average distance is up to 290 km). For this reason, it can be an interesting alternative of study for the Swedish case study to combine transport by road and rail in the case of wood from South Sweden.

## 6 Conclusions

Two case studies of pulpwood production and supply to Spanish and Swedish pulp mills were analysed and compared in order to identify the most environmentally troublesome stages in both wood supply chains. Eucalyptus plantation located in NW Spain was studied in the Spanish case study and two plantations of Norway spruce and Scots pine in the Swedish case study (located in Central and Southern Sweden). System boundaries included all forest operations from site preparation to wood hauling from forest landing to pulp mill gate. The results of the study showed large differences existing between both forest management systems. Logging operations and secondary hauling were identified as the hot spots subsystems in the Spanish and Swedish case studies, respectively. The Swedish case study had lower energy requirements and significantly lower contributions to GWP, EP, AC and PO impact categories. European regulations regarding payload of freight lorries affected the Spanish case study considerably. Higher energy use in Spanish silviculture and logging operations can be linked to the more intensive nature of the managements activities used in eucalyptus stands. Improvement alternatives proposed were: train and lorry transport in wood supply in the Swedish case study and more effective machines in the Spanish case study.

## 7 Future outlook

The results obtained provide valuable information that can assist forest-based industries (not only pulp industry) to improve their environmental performance and to increase sustainability. There are several possibilities for further research; e.g. focus on transport alternatives of pulpwood supply including railway, road and ship for the Swedish case. In addition, in order to get a complete picture of this forest-based industry, studies of pulpwood processing, representative of the “state of art” in the Spanish and Swedish pulp and paper mills considered will be carried out. Another field of interest is a system expansion that includes the substitution of fossil fuel by biofuel (based on forest biomass) and the uptake and sequestration of CO<sub>2</sub> in the productive forests. This will add components towards the direction of having a complete perspective of the forest-wood chain from forest up to the pulp mill.

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